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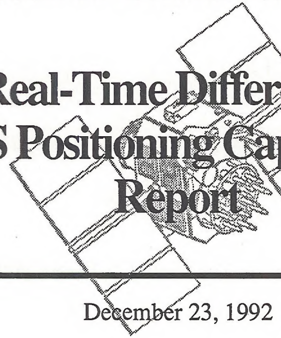

Real-Time Differential GPS Positioning Capabilities Report

December 23, 1992

Prepared for

U.S. Department of the Interior
Bureau of Land Management

ARINC

Bureau of Land Management

Branch of Cadastral Survey

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by ARINC Research Corporation

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1. INTRODUCTION

1.1 PURPOSE

The purpose of this report is to present the present capabilities and limitations of real-time Differential Global Positioning System (DGPS) positioning techniques, including commercially available hardware and software. Emphasis will be placed upon: a) Global Positioning System (GPS) status, b) GPS receiver hardware and software, c) communications hardware and software, d) performance of real-time DGPS systems, e) cost considerations and, f) Bureau of Land Management (BLM) personnel training recommendations.

1.2 GPS OVERVIEW

GPS is a space-based radio navigation and time distribution system. Its mission is to provide precise, continuous, all-weather, three-dimensional (3-D) position, velocity, and timing information to properly equipped air, land, sea, and space-based users. The GPS consists of three segments including the User Segment, the Operational Control System (OCS) Segment, and the Space Segment (SS) (See Figure 1-1).

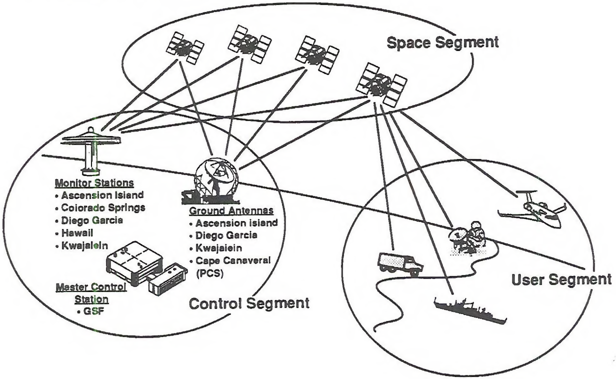


Figure 1-1. GPS Segments

1.2.1 The GPS User Segment

The User Segment consists of all GPS receivers. Receivers vary in size and complexity, though the basic design is rather simple. The typical receiver is composed of an antenna and preamplifier, a radio signal microprocessor, a control and display device, a power supply, and possibly, a data recording device. The GPS receiver decodes the timing signals from the "visible" satellites (four or more) and, having calculated the distance to each satellite, computes its own latitude, longitude, elevation, velocity, and time. This is a continuous process and generally the position is updated on a second-by-second basis then output to the receiver display device and, if the receiver provides data capture capabilities, is stored in the receiver recording unit. In addition, position output data is generally supplied via data ports for input to various other devices for correlation into navigation, timing, or positional information.

1.2.2 The GPS Operational Control System Segment

The OCS monitors, maintains, commands, and controls the GPS satellite constellation. This includes monitoring the performance of the L-band navigation downlinks, updating the navigation message, monitoring the space vehicle (SV) state-of-health (SOH), performing SV maintenance tasks, resolving anomalies, and providing any needed commanding of the satellite constellation.

1.2.2.1 OCS Mission Equipment and Functions

The OCS is composed of the Master Control Station (MCS), Ground Antennas (GAs), Monitor Stations (MSs), associated communications links, and support facilities (see Figure 1-2). The MCS is located at Falcon AFB, CO. GAs and MSs are collocated at Ascension Island (South Atlantic Ocean), Kwajalein Island (West Pacific Ocean), and Diego Garcia (Indian Ocean). The remaining MSs are located at Kaena Point on Oahu, HI and collocated with the MCS at Falcon AFB. There is a Prelaunch Compatibility Station (PCS) located at Cape Canaveral Air Force Station, FL that can act as a backup GA.

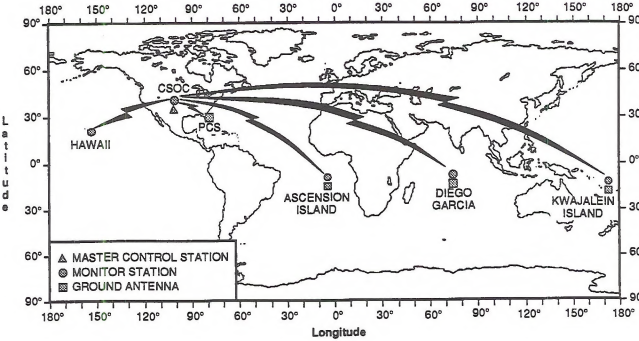


Figure 1-2. GPS OCS

1.2.2.2 Master Control Station

The MCS serves as the GPS mission control center, receiving and processing information from each of the GAs and MSs. The MCS consists of data processing equipment, control display equipment, communications equipment, and the associated software required to perform OCS resource allocation, generate navigation messages, perform satellite health and housekeeping functions, and determine operations capability (OPSCAP) information for both up- and out-channel reporting (see Figure 1-3). In addition, the MCS provides the equipment necessary to support voice and data communications between the MCS and GAs, MSs, PCS, the Defense Mapping Agency (DMA), the U.S. Coast Guard GPS Information Center, and the United States Naval Observatory (USNO). The MCS has the capability to remotely operate up to five GAs and six MSs simultaneously.

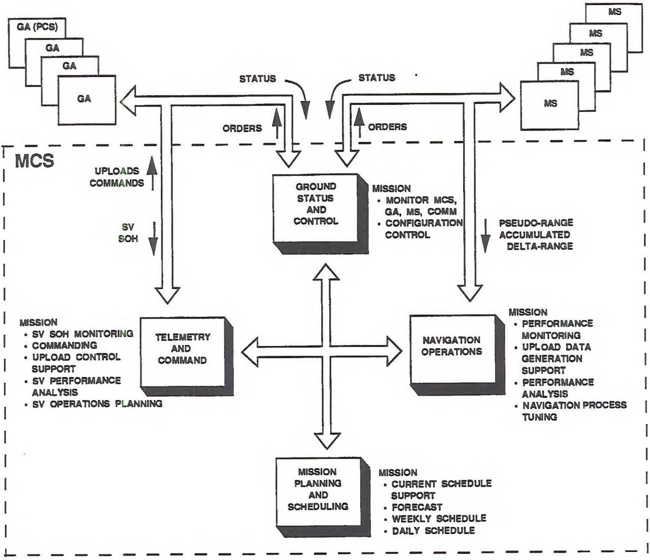


Figure 1-3. Master Control Station Mission Operation Areas

1.2.2.3 Ground Antennas

GAs are active S-band transmission and reception stations that provide the interface to the SVs. They are used to command in real time or perform time-specified command strings and store the most recent eight hours of telemetry for playback. Each GA has a 10 meter parabolic dish with a pointing accuracy of 0.1 degree, and can provide 360 degree horizon to horizon coverage. Dish pointing is driven by MCS estimates of SV position as contained in the navigation messages. The GAs are used by the MCS to observe SV SOH via telemetry, to command on board SV functions, and to upload the navigation message.

1.2.2.4 Monitor Stations

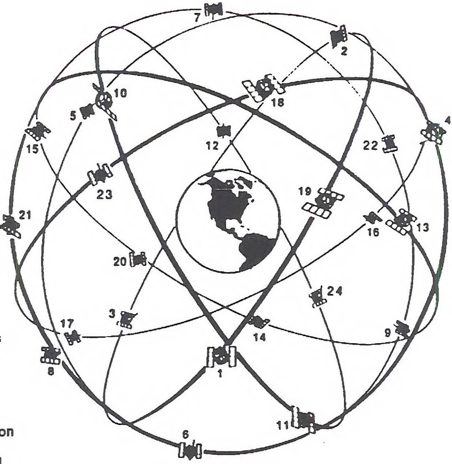
MSs are passive L-band tracking stations which contain receiving units, processors, a multipath-resistant omni-directional antenna, meteorological equipment, high-stability cesium frequency standards, and communications equipment linking the station to the MCS. MSs are capable of receiving L-band signals from 11 satellites and the test transmitter simultaneously. They also collect local meteorological data and perform limited data processing. All tracking and meteorological data is forwarded to the MCS. The meteorological data in conjunction with the multi-frequency tracking data is used to assist in determining atmospheric transmission distortions.

1.2.2.5 Communications

Dedicated communications links are provided from the MCS to each remote site; Ascension, Diego Garcia, Cape Canaveral PCS, Hawaii, and Kwajalein. Dedicated communications links are also provided from the MCS to the DMA. Connectivity to these interfaces is provided by a combination of the Defense Satellite Communications System (DSCS) and Leased Common Carrier (LCC) circuits.

1.2.3 The GPS Space Segment

The GPS Space Segment (SS), when fully operational, will consist of 21 satellites (plus three orbital spares) in 6 orbital planes, with 4 satellites appropriately spaced in each plane (see Figure 1-4). The precise spacing of the satellites in orbit will be arranged to allow a minimum of four satellites in view of any ground point, ensuring worldwide 3-D coverage. Each satellite radiates an L1 and L2 radio frequency navigation message encoded with satellite ephemeris and system time data.



- 21 Satellites
- 3 Spares
- 6 Planes
- 55° Inclination
- 12 hr Period
- 26,550 KM Circular Orbit
- 4 to 7 Satellites Always Visible

Figure 1-4. GPS Constellation

1.2.3.1 Satellites

The GPS satellites consist of two major payloads, the Navigation package and the Nuclear Detonation (NUDET) Detection System (NDS) package, and nine subsystems as shown in Figure 1-5.

The first 11 SVs launched were called Block I SVs and had a design life of five years. They were intended to provide a basic GPS capability for proof of the system and initial limited operational capability. These satellites should be phased out by 1994.

The 28 Block II satellites (9 Block II and 19 Block IIA) were designed to be the fully capable operational units for the GPS constellation. The Block IIs have an increased design life of 7.5 years

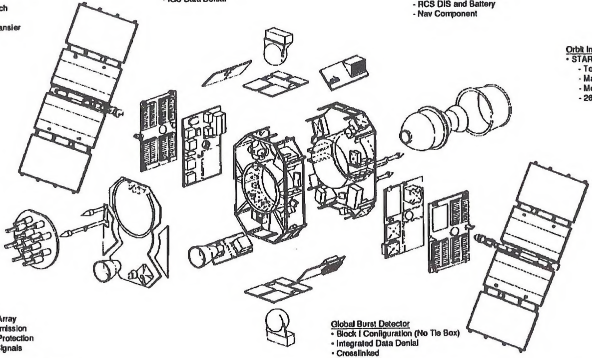


Figure 1-5. GPS Block II Space Vehicle Subsystems

and include the following improvements:

a. Improved reliability

b. Digitized controls

c. Increased and hardened memory capacity

d. 14 day autonomous navigation capability

e. Selective Availability and Anti-Spoof capability

f. A 10 year store of expendables (fuel and battery capacity)

The Block IIA SVs provide an expanded NDS capability and increased automatic on-board systems controls.

There are currently 26 SVs in the acquisition process to be used as replacement satellites for the operational constellation. These Block IIR SVs will have a design life of 10 years and are to provide the following additional capabilities to the constellation:

a. On-orbit autonomous station keeping

b. Upload cross-linking to multiple satellites

c. Increased on board processing capacity

d. Increased radiation hardness

e. 180 day autonomous navigation signal accuracy

f. Laser hardening

g. Increased automatic subsystem control

The Block IIR SVs will have no impact on GPS user equipment.

1.2.3.2 Satellite Signals

The SVs transmit on two radio frequency carriers waves, L1 - 1575.42 and L2 - 1227.6 MHz, in a shaped beam pattern which carries a number of modulated signals on up to 20 MHz of band-width. The relatively low power (50 watts - L1, 12 watts - L2) of the transmitted signals from the SV drives the use of spread spectrum receiver techniques. The high frequency of the carrier bands helps to mitigate adverse atmospheric effects.

The modulated signals or codes transmitted appear random but, in fact, are carefully chosen sequences of binary values generated by mathematical algorithms. These codes are called pseudo-

random noise (PRN) codes and consist of three types, the coarse acquisition-code (C/A-code), the precision-code (P-code), and the Y-code. The C/A-code consists of 1023 binary values or "chips" transmitted at a rate of 1.023 million chips per second. The P-code consists of another sequence of binary values transmitted at 10 times the rate of the C/A-code. The Y-code is an encrypted version of the P-code and when used, replaces the P-code. The L1 carrier normally contains both the C/A and the P-code while the L2 carrier contains the P-code only. The carrier frequencies and codes are modulated to carry the navigation message. The navigation message transmitted by each satellite includes:

a. Satellite health and status so a user can decide whether to accept or reject the data for use in the navigation solution.

b. The handover word (HOW) used to determine time synchronization for transfer from the C/A-code to the P-code.

c. The individual satellite clock correction data and ephemeris parameters which are the most accurate SV data used for position determination.

d. Parameters for correcting ionospheric propagation delays.

e. The almanac which is general clock and ephemeris information on all other satellites in the constellation used for selecting the combination of satellites for the best geometric solution.

1.2.3.3 Constellation

The GPS constellation will consist of 21 SVs plus 3 operational on-orbit spares. The first 21 satellites will be placed in an initial constellation optimized to provide the best possible coverage while the constellation is being built (OPT21). For the Full Operational Capability (FOC) constellation (21+3), the last 3 satellites will be placed in orbit and the original 21 will be shifted to provide a more robust constellation with more satellite failure tolerance. The description of the constellation in standard orbital parameters (see Figure 1-6) is shown in Tables 1-1 and 1-2. The constellation is comprised of six planes, A-F, at an inclination to the equator of 55 degrees with four satellites spaced appropriately in each plane. The satellites have an orbital period of 12 sidereal hours at an altitude of approximately 11,000 miles. There are currently 20 satellites on orbit as shown in Table 1-3.

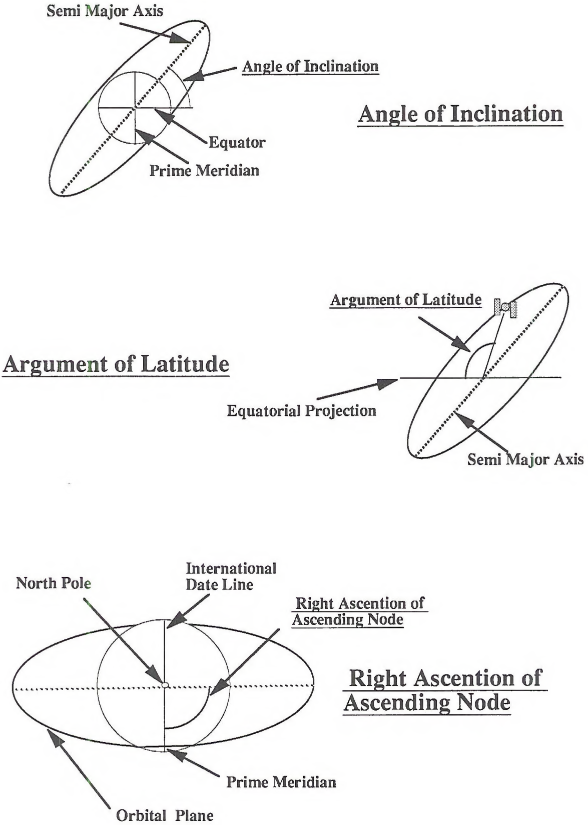


Figure 1-6. Orbital Parameters

Table 1-1. Reference Orbit Parameters

REFERENCE ORBIT PARAMETER	NOMINAL VALUE	REQUIRED TOLERANCE
SEMIMAJOR AXIS, Km	26,559.8	+/-50 KM (1) (2)
ECCENTRICITY, deg	0.0	0.0 to 0.020
INCLINATION, deg	55.0 (3)	+/-1 (2)
RIGHT ASCENSION OF ASCENDING NODE, deg	(3)	+/-2 (+/-180)
ARGUMENT OF PERIGEE, deg	0.0	+/-180
ARGUMENT OF LATITUDE AT EPOCH, deg	(3)	+/-180 (3)
TIME OF EPOCH	(3)	N/A

(1) Block II/IIA SVs shall operate within +/- 17 km of nominal.
(2) The semimajor axis and orbital period shall be adjusted to maintain the relative spacing of the SV groundtrack equatorial crossings to within +/- 1 deg of chosen values, with one year or more between orbital adjustments. The nominal values shown provide stationary groundtracks.
(3) See Table 1-2.

Table 1-2. Orbital Position Assignments

ORBITAL POSITION(2)	RIGHT ASCENSION OF ASCENDING NODE	ARGUMENT OF LATITUDE, deg(1)	
		OPT21	21 + 3
A1	317.0	280.7	280.7
A2	317.0	59.7	310.3
A3	317.0	176.9	60.0
A4	317.0	314.2	173.4
B1	17.0	350.7	339.7
B2	17.0	88.7	81.9
B3	17.0	219.7	115.0
B4	17.0	----	213.9
C1	77.0	19.7	16.0
C2	77.0	158.7	138.7
C3	77.0	262.4	244.9
C4	77.0	125.2	273.5
D1	137.0	57.9	42.1
D2	137.0	176.4	70.7
D3	137.0	306.7	176.8
D4	137.0	----	299.6
E1	197.0	101.9	101.7
E2	197.0	198.7	200.5
E3	197.0	337.4	233.7
E4	197.0	240.7	335.9

Table 1-2. Orbital Position Assignments (Continued)

ORBITAL POSITION[2]	RIGHT ASCENSION OF ASCENDING NODE	ARGUMENT OF LATITUDE, deg[1]	
		OPT21	21 + 3
F1	257.0	132.7	142.2
F2	257.0	262.9	255.6
F3	257.0	21.4	5.3
F4	257.0	----	34.8

(1) - EPOCH: 0000 hrs UTC, 1 July 1990
- GREENWICH HR ANGLE: $18^h\ 35^m\ 09.4134^s$
- REFERENCED TO FK5/J2000.00 COORDINATES

(2) Orbital position IDs are arbitrarily numbered for each constellation.

Table 1-3. Constellation Status

PRN	SVN	TYPE (BLOCK)	HEALTH	ORBITAL PLANE	CLOCK
2	13	II	Up	B-3	Cs
3	11	I	Up	C-4	Rb
11	8	I	Up	C-3	Rb
12	10	I	Up	A-1	Rb
13	9	II	Up	C-1	Cs
14	14	II	Up	E-1	Cs
15	15	II	Up	D-2	Cs
16	16	II	Up	E-3	Cs
17	17	II	Up	D-3	Cs
18	18	II	Up	F-3	Cs
19	19	II	Up	A-4	Cs
20	20	II	Up	B-2	Cs
21	21	II	Up	E-2	Cs
23	23	IIA	Up	E-4	Cs
24	24	IIA	Up	D-1	Cs
25	25	IIA	Up	A-2	Rb
26	26	IIA	Up	F-2	Cs
27	27	IIA	Up	A-3	Cs
28	28	IIA	Up	C-2	Cs
32	32	IIA	Not Operational	F-4	N/A

PRN = Pseudo Random Number (Code number assigned to a specific satellite)
SVN = Space Vehicle Number (Actual satellite side number)
Cs = Cesium
Rb = Rubidium

1.2.3.4 GPS Schedule

The current plans call for full operational capability when 21 Block II SVs are in orbit, sometime in 1993. The last SV placed in orbit was SVN #32 launched November 22, 1992, and expected to be operational by December 20, 1992. The next SV scheduled for launch is SVN #29 at a date no earlier than December 15, 1992. The constellation build plan tentatively calls for launches every 90-

120 days until the constellation is complete and all Block I SVs are replaced with Block II SVs (see Table 1-4). After the constellation is established, new SVs will be launched on an as-required basis. It is expected that a minimum of 60 days notice will be required for a replacement launch. Based on the expected design life of the SVs a tentative schedule for replenishment of the constellation has been developed and satellites and launch vehicles have been placed under contract to support this plan.

Table 1-4. Planned Launch Schedule (as of 1 December, 1992)

LAUNCH ORDER	SVN	LAUNCH DATE	PLANE	TYPE
II-17	29	15 DEC 92	D-4	IIA
II-18	30	2 FEB 93	B-1	IIA
II-19	TBD	23 MAR 93	C-4	IIA
II-20	TBD	5 MAY 93	C-3	IIA
II-21	TBD	JUL 93	A-1	IIA
II-22	TBD	SEP 93	B-4	IIA
II-23	TBD	OCT 93	F-1	IIA
II-24	TBD	15 MAR 93	C-1	IIA

Launch dates and planes are subject to change
Launch dates listed are "not earlier than"

1.2.4 Specified Accuracies

GPS accuracies as specified in the Federal Radio-Navigation Plan (FRP) are shown in Table 1-5. The GPS system specifications state that the GPS will provide accuracies of 16 meters Spherical Error Probable (SEP) and time transfer of less then 100 nanoseconds (1 sigma). These various terms of accuracy are essentially statistical values based on a standard Gaussian distribution of values. Table 1-6 expresses these various specifications in terms of a percentile value. In other words, with percentile values, if a circle or sphere of the specified radius is drawn around a known given point, the stated percent of all GPS readings taken from a receiver resting on this known given point will fall within the circle or sphere. The civil applications of GPS require a commitment by the U.S. government to supply the GPS signals to the minimum specifications as defined in the FRP.

1.2.4.1 Standard Positioning Service

A compromise between the military concerns about high accuracy positioning and the civil

Table 1-5. GPS Characteristics (Signal-in-Space)

ACCURACY*			AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSION	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
PPS** Horz - 17.8m Vert - 27.7m Time - 100ns	Horz - 17.8m Vert - 27.7m	Horz - 17.6m Vert - 11.7m	Expected to approach 100%	Worldwide continuous (PDOP ≤ 6)	98% probability that a 21-satellite constellation will be operating	Essentially continuous	3D + Velocity + Time	Unlimited	None
SPS Horz - 100m Vert - 156m Time - 167ns	Horz - 100m Vert - 156m	Horz - 28.4m Vert - 44.5m	Expected to approach 100%	Worldwide continuous (PDOP ≤ 6)	98% probability that a 21-satellite constellation will be operating	Essentially continuous	3D + Velocity + Time	Unlimited	None

* *Horizontal 2 drms; Vertical 2 Sigma; Time 1 Sigma.*
** *For U.S. and Allied military, U.S. Government, and selected civil users specifically approved by the U.S. Government.*

Table 1-6. GPS Accuracy Conversions

2 drms	Twice the distance root mean square (2 dimensional), converts to the 95th percentile for GPS usage
1 Sigma	(Time) 68th percentile, (2-Dimensional) 63rd percentile
2 Sigma	(Vertical) 95th percentile
SEP	Spherical error probable, converts to the 50th percentile (three dimensional)
CEP	Circular error probable, converts to the 50th percentile (two dimensional)

community needs for positioning services has resulted in a deliberate degradation of the GPS signal accuracy. This degradation is limited in peace-time to values established in the FRP. The Standard Positioning Service (SPS) is the standard specified level of positioning, velocity, and timing accuracy that is available, without qualification or restrictions, to any user on a continuous worldwide basis. The accuracy of this service will be established by the U.S. Department of Defense (DOD) based on U.S. security interests. When GPS is declared fully operational (in 1993), the DOD plans to provide, on a daily basis at any position worldwide, horizontal positioning accuracy within 100 meters 2 drms (95 percent probability) and within 300 meters with 99.99 percent probability. The SPS characteristics are listed in Table 1-5.

1.2.4.2 Precise Positioning Service

For civilian needs where higher accuracy than the SPS is required, where it is in the U.S. government interest, and where there is no viable alternative service, access to the full GPS accuracy can be obtained with permission from the U.S. Department of Defense with the U.S. Department of Transportation. Access to the full GPS accuracy is through the Precise Positioning Service (PPS). PPS is the most accurate positioning, velocity, and timing information continuously available, worldwide, from the basic GPS. This service will be limited to authorized U.S. and allied Federal Government and military users and to those civil users who can satisfy U.S. requirements. Unauthorized users will be denied access to PPS through the use of cryptography. P-code capable military user equipment will provide a predictable positioning accuracy of at least 17.8 meters (2 drms) horizontally and 27.7 meters (2 sigma) vertically. Timing/time interval accuracy will be within 100 nanoseconds (1 sigma). The PPS characteristics are listed in Table 1-5.

1.2.5 GPS Selective Availability and Anti-Spoofing

GPS has the potential of supplying positioning services to anyone with a receiver. Since GPS was developed as a military tool, the high accuracy positioning capabilities have a designed military value. To prevent a potential adversary from having access to the GPS, especially in time of conflict, the Selective Availability (SA) and Anti-Spoofing (A-S) techniques were developed for GPS.

1.2.5.1 Selective Availability

The method used to intentionally degrade the quality of the GPS signals is called SA. SA is a

distortion of the ephemeris and/or timing signal that is introduced with encryption techniques into the satellite navigation message and sent from the SVs. The amount of distortion is variable and can range from little or no impact on the signal, to rendering the GPS signal essentially useless with errors in excess of a nautical mile. Standard military receivers are designed to interpret the encryption and give full GPS accuracies at any time. There is a process available to make military accuracies available to other government agencies and under special circumstances to civil entities.

1.2.5.2 Anti-Spoof

The U.S. military designed an encrypted capability into the GPS to prevent an adversary from causing significant errors in the GPS by falsely emulating GPS type signals. The method used to do this is called A-S. A-S is an encryption of the P-code that requires a special security module in the receiver in order to use it. Use of A-S effectively denies P-code access to anyone who does not have the security module.

2. DIFFERENTIAL GPS

Differential positioning techniques have been developed to obtain greater accuracy from the GPS than was originally intended in the system design. Additionally, differential techniques can overcome the effects of SA and A-S in a limited operating area. Differential positioning can be divided into two categories, post processing techniques and real-time techniques. To understand the differential GPS positioning techniques, a basic understanding of the GPS positioning theory is necessary.

2.1 FUNDAMENTALS OF SATELLITE POSITIONING

GPS positioning is accomplished by calculating the distance to a set of four or more SVs through radio signal time delay methods. The distance to each satellite from the receiver is determined and compared to the known (or readily calculated) position of the respective satellites. With the range vectors between the unknown position of the receiver and the known or predicted positions of the set of satellites, it is possible to derive the position of the receiver within an earth-centered/earth-fixed reference grid.

2.1.1 General Positioning

The position of a point on or above the Earth's surface can best be described in terms of two general reference frames. In the first case, the position is defined with respect to a well-defined coordinate system, commonly a geocentric system (i.e., a system whose point of origin coincides with the center of mass of the Earth). This is known as point positioning. Alternatively, the point can be described using relative positioning in which another surface point of known location, such as a benchmark or control monument, serves as the origin of a local coordinate system in which the point can be defined.

Positioning from satellite ranges is based on the same principle used in traditional terrestrial surveying methods. Simply stated, by measuring the distances to three noncoincident points of known positions, a triangulated solution can be obtained. GPS extends this general concept to a space-based system, measuring the distances to three or more nonplanar satellites and triangulating the position of a survey point accordingly. Analogous to the point and relative position modes described above, there are two modes of satellite positioning, absolute and

differential. These two operational modes of GPS vary significantly in terms of methodology and accuracy. Differential positioning will be discussed in Paragraph 2.2.

2.1.2 Absolute Positioning

This mode of positioning relies upon a single receiver station. It is referred to as "stand-alone" GPS because, unlike differential positioning, ranging is done strictly between the satellite and the receiver station and does not use a ground-based reference station to assist with the computation of error corrections. As a result, the positions derived in absolute mode are subject to errors inherent in satellite positioning. Overall accuracy of absolute positioning using C/A-code is considered to be no better than 26 meters CEP.

2.1.3 Measuring Range Vectors

A variety of techniques can be used to measure earth-to-satellite range vectors. GPS utilizes what is referred to as one-way radio ranging to determine satellite distances. Each GPS satellite and all GPS receivers simultaneously generate an identical PRN signal. The timing of the satellite radio signal transmissions is calibrated by atomic clocks aboard each satellite. Each satellite transmits the coded signal towards earth, where it can be captured by the user's receiver.

When a coded satellite signal arrives at the GPS receiver, its signal is matched to that generated by the receiver. The receiver measures the time difference between identical segments of the satellite-generated and receiver-generated signals in order to determine the length of time that was taken for the signal to travel from the satellite to the receiver. By multiplying this time by the speed of light, the distance or range vector between the satellite and the receiver can be determined.

A GPS receiver is capable of making only two types of range vector measurements, pseudo-range and carrier phase.

2.1.3.1 Pseudo-Range

The concept of pseudo-range vectors is relatively simple and is the measurement made by most GPS receivers. It is the apparent range between the satellite and the receiver and is called pseudo-range because it contains known biases and errors. Pseudo-range is calculated

by measuring the time shift required to line up matching segments (called code epochs) of satellite generated and receiver-generated code and multiplying by the speed of light. (See Figure 2-1.) Ideally, the time shift is the difference between the time of signal transmission and the time of signal reception. In fact, the relative motion of the satellite with respect to the receiver (the Doppler effect) causes the two time frames to differ, which introduces a bias into the measurement. Lack of precise synchronization between the satellite clock and the receiver clock can also create a bias, which affects all measurements made with a specific receiver. These biased, time-delayed measurements are referred to as pseudo-ranges.

A rule of thumb for estimating the precision of pseudo-range measurements is that the precision will be 1 percent of the period between successive code epochs. For the P-code, successive epochs are 0.1 microsecond apart, implying a measurement precision of 1 nanosecond. When multiplied by the speed of light, this implies a range measurement precision of 30 centimeters. For the C/A-code, the numbers are 10 times less precise, which provides a range measurement precision of 3 meters.

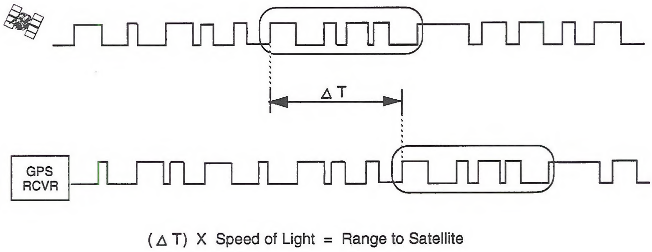


Figure 2-1. Pseudo Range Determination

2.1.3.2 Carrier Phase

The received frequency of a GPS satellite signal is different from the frequency transmitted by the satellite, and is continually changing due to the Doppler effect. Carrier phase range measurements are made by comparing the received satellite carrier frequency (L1 or L2) to a receiver generated frequency. To make this measurement, the receiver must be able to determine the difference in carrier wavelengths (or cycles) between the satellite and receiver signals. Because the wavelength of the carrier is much shorter than the wavelength of the PRN codes, the precision of carrier phase measurements is much higher than the precision of P-code or C/A-code pseudo-ranges. For the GPS L1 carrier signal, the wavelength is about 20 centimeters. Using the rule of thumb for precision estimation of measurements, carrier phase measurements can be made to about one percent of the wave-length. This implies a measurement precision of 2 millimeters which permits very high precision positioning for certain applications.

Obtaining the initial number of integer cycles of the carrier between satellite and receiver is very difficult, if not impossible. Realistically, an assumption must usually be made about the initial (unknown) cycle ambiguity. Once this assumption is made, it is critical that an integer cycle count be maintained as the satellite-to-receiver range changes with time. When an interruption occurs in reception of the satellite carrier frequency ("loss of lock"), the receiver effectively "loses count" of the number of cycles between satellite and receiver signals. This is known as cycle slip. Overcoming initial cycle ambiguity and minimizing cycle slip problems typically requires a very high quality GPS receiver.

2.1.4 Hardware

There are two broad groups of GPS receivers, sequential tracking and simultaneously tracking. Sequential tracking receivers track and monitor the satellite signals of four satellites selected for a position solution one after another in sequence in order to be able to calculate a position. Simultaneous or continuous receivers have multiple channels allowing data to be gathered from up to all satellites in view at once. The simultaneously tracking receivers provide a position much quicker than the sequential tracking receivers and usually provide significantly

higher accuracy with a lower signal to noise ratio. Various techniques of multiplexing and signal processing have helped to improve the performance of both types of receivers.

As a general guideline, sequential tracking receivers are either one or two channel receivers that provide low dynamic, moderate accuracy positioning, that is relatively succeptable to terrain interruptions. These receivers are relatively lower in cost than the multiple channel simultaneous receivers and are often lighter and more portable and therefore used for navigation purposes. The multi-channel simultaneous receivers provide higher degrees of accuracy, are less succeptable to terrain masking, can provide extremely high dynamic capabilities, provide multiple methods of signal reception (i.e., dual frequency, C/A-code, P-code, and carrier phase), and in some cases, can track all satellites in view. These receivers are generally higher in cost and are used in either high dynamic, military, or survey applications.

2.2 FUNDAMENTALS OF DIFFERENTIAL GPS POSITIONING

Differential GPS (DGPS) positioning uses two or more receivers to facilitate the determination of a geographic position relative to a known earth surface point. One receiver is used as a reference receiver and is positioned either at a known geodetic control point or at a self determined control point. A GPS position is derived and then compared to the control point coordinate.

The difference between the GPS determined position and the known control point position allows a correction factor to be calculated and applied to any other GPS units used in the same area and at the same time. Inaccuracies in the control point's GPS determined coordinate are directly related to and can be used to correct the satellite positioning coordinates determined by the other GPS receivers. Error corrections derived by the reference station vary rapidly as the factors propagating position errors change over time. This comparison error correction allows for a considerable amount of error to be negated, potentially as much as 90 percent.

The assumption made when operating in differential mode is that bias and random error factors affecting the reference station are equally affecting roving units operating with the reference station. For this fundamental assumption of common errors to be true, the units must be tracking the same satellites and must be within a practical range of approximately 300 miles

from the reference receiver. After 500 miles, the errors start to become significant although theoretically they could be valid in excess of 1000 miles. The range restriction is imposed due to two factors which contribute to the "spatial decorrelation" of the errors. The first range-reducing factor is that for widely separated stations the direction cosines from satellite to receiver may differ, causing a differing observation of satellite ephemeris error. Second, the error produced by atmospheric disturbances to the C/A-code transmission is dependent upon the path the transmission takes through the atmosphere (i.e., different paths may have different errors). This error at geographically separated points may be significant because atmospheric propagation errors can account for as much as 60 percent of total GPS positioning error.

Differential GPS positioning can be conducted with either real-time or post processing methods. Real-time DGPS will be discussed in Section 2.3. The types of differential positioning, static or kinematic, use either geographical error corrections or pseudo-range error corrections as discussed below.

2.2.1 Post Processing

The error corrections used for differential positioning can be determined by either post processing or real-time methods. In a post processing scenario, all data from the reference receiver and the roving receivers are recorded on magnetic media and taken to a data processing facility. Post processing involves the use of data filtering and smoothing routines. The Kalman filter and smoothing routines are applied recursively to the data, forward and backward. This reduces the variability of positions at a given collection point. The filtering and smoothing routines are used on both the roving receiver and the reference receiver data streams. The filtering reduces the effect of signal noise and multipath errors. Post processing can reduce the standard deviation of the positioning error to 1.5 meters or less from a typical accuracy of 3 to 5 meters found in some differential positioning systems. The highest levels of accuracy available from GPS are obtained when post processed differential techniques are used.

2.2.2 Static Positioning

GPS can be used to position both stationary and moving objects in either real-time or post

processed mode. If the roving receiver is stationary (static positioning), multiple range vectors to each of the satellites used in the position determination are calculated and the differential error corrections are factored in. Such redundant observations provide a higher level of accuracy for the determined position. Typically, the data from the roving station is collected over a 3 to 5 minute period. This provides the optimal data and additional collection time will not significantly enhance the accuracy.

2.2.3 Kinematic Positioning

When the roving receiver is moving (kinematic positioning), instantaneous positions or fixes are determined. Ideally, these are from four range vectors observed simultaneously with the differential error corrections that are either factored in immediately or post processed. There is generally no redundancy in the data and normally, a real-time solution of one fix at a time is used. The resulting string of fixes can also be recorded and post processed using a number of existing smoothing operations to improve the quality of the positional fixes.

2.2.4 Geographical vs. Pseudo-Range Corrections

There are two types of positional error corrections; geographical corrections to the computed latitude, longitude, and elevation, and corrections to the pseudo-ranges between the satellites and the GPS receivers. There are significant differences between these two error correction methods that have implications on the utility of the data collected. GPS receiver units, while operating in either static or dynamic mode, are constantly scanning available satellites and locking onto the best configuration for accuracy. Reference stations are operating in the same manner, however, they may not necessarily always lock onto the same set of satellites at any given moment. The geographic correction method requires that positioning be based on the same set of satellites at both the reference and roving stations. Receivers record information on the constellation in use along with the positional coordinates derived. This allows for a comparison of constellations used during post processing. With the geographic correction method, if the constellations used do not match, that fix must be thrown out and not used in the final coordinate computation. Given that as many as 200 coordinate fixes may be collected for a point position over a 3 to 5 minute recording session, for static positioning, some loss of individual data points may not significantly affect the coordinate

solution for a point. However, this method is less suitable for kinematic positioning where loss of position points may be significant.

The pseudo-range method is more complicated since a range correction factor for each satellite must be computed (four or more ranges to be corrected), and the correction must compensate for clock bias which will differ between each receiver station. Pseudo-range correction is potentially more flexible than the geographic correction method. If pseudo-range corrections are performed on all satellites in view, then the receivers do not have to be locked on to the same four satellites at any given time. The correction factors for each particular satellite are applied to whatever group of satellites that the roving receiver has selected for position determination at any given time. Using this method, there should be no data points lost due to satellite selection at the roving receiver.

2.3 FUNDAMENTALS OF REAL-TIME DGPS

For real-time DGPS positioning, error corrections are calculated at the reference receiver or monitor station and then transmitted by radio, phone, or other electronic media to the roving receivers. The roving receivers must have the capability of receiving the corrections and applying the corrections to their position determination. These corrected positions are used at the time to determine a series of "fixes" or may be recorded for future use or verification. Normally, real-time DGPS is not as accurate as post processed DGPS because the extensive filtering and smoothing routines are not applied to the data. As a general practice, pseudo-range corrections rather than geographic corrections are used for real-time DGPS systems.

Real-time differential positioning requires a dedicated communication link (such as VHF-FM radio) to transfer the error correction to the roving receivers. The roving receivers require a radio receiver hardware option of some type to be able to receive these error corrections. (See Figure 2-2.) The differential error correction data is typically transmitted at a low data rate (50 bits per second minimum) in a standard data format defined by the Radio Technical Commission for Maritime Services (RTCM) special committee (SC)-104. Depending upon the needs of a user and the equipment capabilities, this data rate may be increased significantly or even sent in burst mode. Although the RTCM SC-104 format is standard and designed to be compatible with GPS signal formats, some

equipment manufacturers have developed their own formats for differential error correction messages. This may restrict the interoperability of some GPS receiver equipment.

2.3.1 Pseudo-Satellites

An alternative real-time correction scheme transmits data from the reference station in the

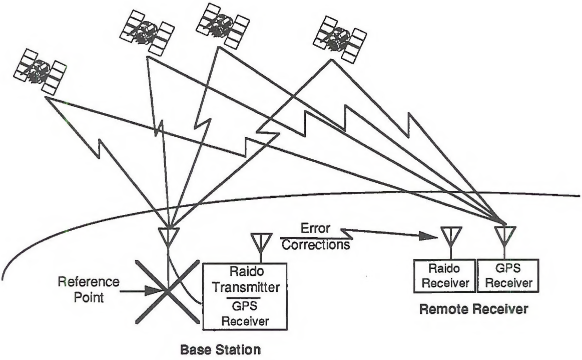


Figure 2-2. Real-Time DGPS System

same frequencies and formats as the satellites themselves, this is called pseudo-satellite approach. Special software is required in the roving receiver to be able to recognize the pseudo-satellite (it must have a PRN code different from the actual satellites). This software must be able to differentiate the error corrections and apply them to a position solution. Pseudo-satellite error correction data is sent at 50 bps to match the satellite navigation message data rate. The main advantage to the pseudo-satellite approach is that no special radio receiver equipment is required to be able to access the error correction messages by the roving receivers. However, because of the radio frequencies used, this is essentially a line-of-sight method with accuracies under the best of conditions in the 3 to 5 meter range.

2.3.2 Error Correction Processing

Real-time DGPS operations are not actually instantaneous. The navigation signals generated

by the satellite (orbital parameters) have an associated Issue of Data Ephemerides (IODE) designated by the GPS control segment. This IODE is generated so that the satellite ephemeris information (used by the receiver to calculate the satellite position) can be identified with its time of transmission. A receiver can perform position solutions using ephemeris information previously broadcast by a satellite. When this ephemeris information is updated (new IODE) the receiver may continue to use the old ephemeris information. This will affect the differential error corrections generated by the monitor station.

The monitor station transmits the IODE for each particular error correction message, along with that error correction message. The remote receiver will not use the error messages from the monitor station unless the IODE of the error correction message matches the IODE of the orbit parameters in the remote receiver. This means that the remote receiver must store orbit parameters until the correction message with the matching IODE can be received from the monitor station.

A typical correction message is 420 bits long (6 satellites plus the preamble) and is sent at 50 bps. If more satellites are included in the error correction messages, the data will take about 1.2 seconds longer per satellite. In addition, many differential processing techniques use smoothing algorithms that may use from 5 to 25 seconds of error corrections prior to updating the error projections at the remote receiver. The combination of smoothing techniques and data transmission rates results in a series of continuous corrections at the remote receiver that can lag 2 to 25 seconds or longer behind the actual satellite navigation signals received at the remote receiver. The error correction messages are used to build a correction prediction table for pseudo-range corrections on each satellite. These predictions indicate the expected errors in the satellite navigation signal being received based on what the errors were within the past minute or so. (See Figure 2-3.)

2.3.3 Area of Coverage

The distance from the reference or monitor station has a direct effect on the accuracy of the system. In a practical sense, ground based real-time DGPS systems work best within a 300 mile radius of the monitor station. Theoretically, the error correction messages should be valid for ranges up to around 1,000 miles. The transmission medium characteristics in conjunction with the roving receiver radio reception capabilities are the primary area limiting factor in a real-time DGPS system.

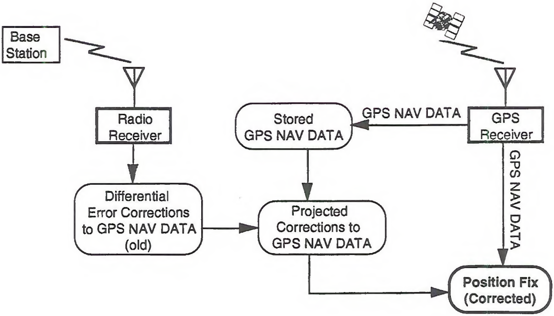


Figure 2-3. Real-Time DGPS Processing (Remote Receiver)

The radio frequency chosen for the error correction transmissions as well as the location of the transmitting antenna determines the "visibility" of the error correction messages to the roving receiver. These visibilities can be divided into three categories, short range (100 miles or less), full practical range (out to 300-500 miles), and wide area or extended range (out to 1,000 miles).

Short range applications can be served by VHF and UHF radios (essentially line of sight applications), cellular telephones (within the local area serviced), pseudo-satellites (line-of-sight applications), and low power HF transmissions. Full practical range applications can be served by HF and VHF radios (10 to 100 MHz) with medium power output or by networked HF/VHF radios with over the horizon capability.

Wide area or extended range applications for real-time DGPS have not yet been developed. Several systems are proposed which would use either communication satellite transmissions, leased portions of the FM commercial broadcast radio spectrum, or dedicated DGPS satellites. The U.S. Coast Guard is in the process of creating a wide area system by developing a series of practical range systems with overlapping coverages as shown in Figure 2-4. Another proposed wide area system, the Global Navigation Satellite System (GNSS) would use separate geosynchronous satellites to provide GPS corrections and GPS integrity information to the aviation community. GPS error

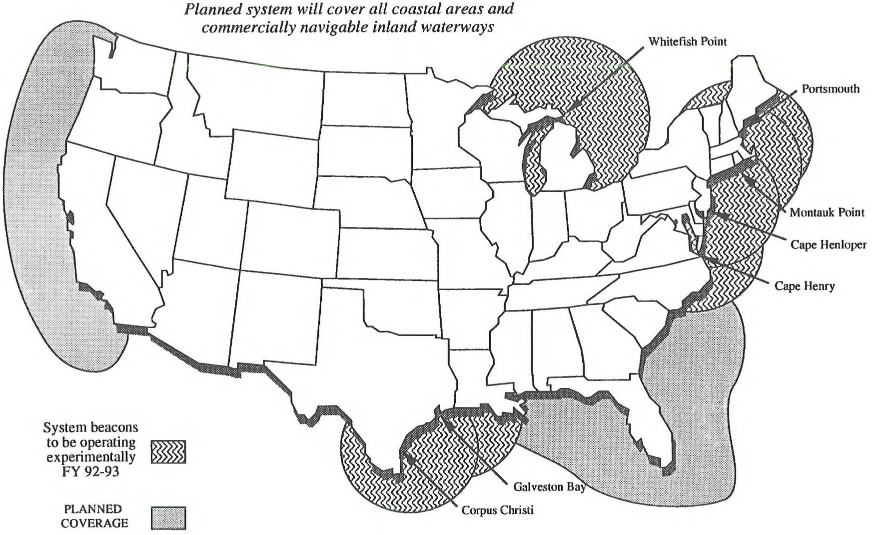


Figure 2-4. U.S. Coast Guard Differential GPS Beacon System

corrections and integrity information would be determined at a base station and then up-linked to a geosynchronous satellite for re-transmission to the users. This down-linked information may be protected by encryption techniques to restrict it to authorized or paying customers.

Some null areas will occur in real-time DGPS coverage due to terrain factors (i.e., heavy foliage, hills, valleys, buildings, etc.) and electrical interference sources (i.e., high voltage power lines, lightning, commercial radio stations, high power radars, etc.). These are the same type of factors that affect any radio broadcast.

2.3.4 Real-Time System Accuracy

Typical real-time DGPS accuracies are within the 2 to 10 meter range. These accuracies are obtained using the C/A-code SPS capability only. Higher levels of accuracy can be obtained through several techniques:

a. Use of the P-code in addition to the C/A-code is inherently more accurate because of the higher modulation rate of the P-code. Typical accuracies using P-code and C/A-code (single frequency) are within the 2 to 4 meter range.

b. Use of dual frequency L1 and L2 in combination with C/A-code and P-code helps to mitigate atmospheric transmission errors in addition to providing dual trace of the P-code. Dual frequency techniques are typically within the 1 to 3 meter range.

c. Although slower, and subject to cycle slip ambiguity, carrier phase techniques yield the highest accuracies. With internal smoothing techniques applied, carrier phase techniques can yield accuracies in the sub-meter range. However, the position solutions are typically 25 seconds to 1 minute behind the actual positions and are not generally suited to highly dynamic positioning applications. Real-time DGPS carrier phase techniques usually require more processing power (i.e., a high end PC) at the monitor station to develop the error correction messages.

d. Increasing the SV navigation message update rate of the monitor station and the resultant error correction messages is one way to improve the accuracy of a real-time DGPS system. A typical differential system error will "drift" at .25 meters per second, so the higher the update rate, the lower the inherent drift error.

Depending upon the methods used and the equipment capability, real-time DGPS can produce accuracies from the sub-meter range to the typical 2 to 10 meter range. (See Figure 2-5.)

2.4 REAL-TIME DIFFERENTIAL GPS RECEIVERS

GPS receivers used in real-time DGPS applications are typically multi-channel receivers

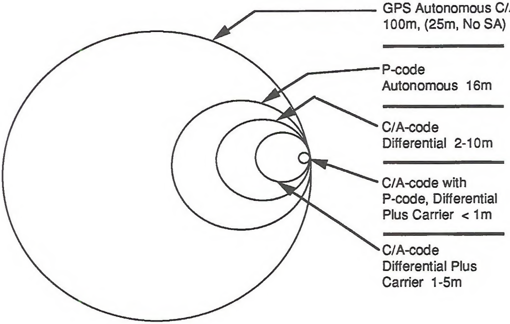


Figure 2-5. Real-Time Positioning Accuracies

operating in a continuous mode. These receivers are capable of simultaneously monitoring four or more satellites continuously without the need to delete functions while acquiring another satellite. They are designed in 4, 5, 6, 8, 10, and 12 channel configurations. The additional channels offer the following advantages in DGPS positioning:

a. All satellites in view may be tracked allowing a position solution using the best combination of satellites (in the full constellation there will normally be between six and nine satellites in view the majority of the time).

b. A channel not used to track a satellite may be used to acquire and track the error correction messages.

c. Spare channels can be used to track carrier phase data for a specific satellite to be used in

conjunction with the C/A or P-code data for that satellite, this significantly enhances positioning accuracy.

d. The additional channels permit simultaneous signal processing and significantly increase the signal-to-noise ratio of the individual satellite navigation messages.

There are two types of GPS receivers used for real-time DGPS positioning, the monitor or base station and the roving receiver. Although these receivers may be identical, typically, the base station is a higher quality (survey type) receiver capable of generating the error correction messages. This base station is coupled with a transmission source of some type to send the error correction messages and may include a separate processing capability such as a high end PC type computer. The roving receivers are generally less capable (and therefore cheaper) than the base station. They are coupled with a receiving device (radio, cellular modem, etc.) and have the capability to process the error correction messages. In some cases a portable laptop type computer is used with the roving receiver to attain greater accuracy through the application of smoothing routines not available in the receiver.

The current real-time DGPS receivers available on the market are described in Appendix 1.

2.5 REAL-TIME DGPS SOFTWARE

The software used for real-time DGPS applications is generally receiver manufacturer specific because the processing is normally done within the receiver itself. However, several smoothing routines for general DGPS rather than real-time DGPS may be used if external processing capability is provided. In addition, a host of commercial software is available that facilitates interfacing positional data (from any source) with Computer Aided Design/Geographic Information Systems (GIS) and electronic mapping systems. A partial listing of this software is found in Table 2-1.

Table 2-1. Types of GPS Receiver Software Interfaces

MANUFACTURER	SOFTWARE
Ashtech	Mission planning, Dynamic calibration, GPPS, Fillnet, GPS-CADD Process, Prism, Mult-site mission planning, GIS Post Processing
Magellan	ARC/INFO, Autocad/DXF ERDS, Grass
Motorola	GIS, Trailane
Navstar	Map Info
Trimble	Date Com, DCA, AutoCAD, ARC/INFO, Intergraph, GPSurvey, PFinder, TRIMVEC Plus, TRIMMAP, NGS-CR88BB-MAKEG

3. REAL-TIME DGPS COMMUNICATIONS

A key element to real-time DGPS is the communications devices used to transmit and receive the differential corrections. There are several mediums used to accomplish this task including; dedicated radio transmissions, radio transmissions piggybacked on other systems (i.e. navigation beacons, etc.), cellular phone, and satellite transmissions.

3.1 FUNDAMENTALS OF REAL-TIME DGPS COMMUNICATIONS

Real-time DGPS positioning is dependent upon the communications medium to be able to function. The primary considerations when selecting the radio transmission capability for a real-time DGPS system are dependent upon the overall requirements of the system. There are three main requirements of the overall real-time DGPS system that drive the design of the transmission system; accuracy, area of coverage, and portability.

First, the accuracy requirements determine the number and frequency of messages that must be sent to achieve a given level of accuracy (i.e., the higher the accuracy, the more messages required). In addition, the dynamics requirements of the system in combination with the accuracy requirements drive the message update rate of the system. A high update rate of once per second or less is required for high dynamic (aircraft), high accuracy systems. Lower update rates of up to about once per 30 seconds can be used for less demanding systems (surface vehicles). The more messages required in a given period of time result in a wider bandwidth to support a given transmission rate. A typical navigation type differential system (2-10 meter accuracy) uses a 50 bits per second transmission rate with a bandwidth of 1 kilohertz or less. For a high accuracy system, the bandwidth can be 2 to 4 kilohertz or larger with transmission rates greater than 1,000 bits per second.

Second, the area of coverage requirements drive the frequency and power output of the transmission system as well as the type and placement of the system antennas. As discussed in 2.3.4 the type of transmission system varies according to the desired area of coverage. The larger system areas of coverage require a HF/low VHF frequency with relatively high power output while the smaller areas of coverage can be serviced by relatively low power VHF/UHF line-of-sight transmis-

sion systems. The positioning of the antennas determines the line-of-sight path to the roving receivers, (i.e., the higher the antenna the longer the range).

Third, the portability requirements of the roving receivers drive the size, weight, power consumption, and antenna design for the roving receiver radio unit. If the roving receiver is to be man portable, then generally the radio unit will be a small, low power, line-of-sight unit with a "stub" antenna. Roving receivers to be used in vehicles or on board vessels have less restrictions and may run the gamut from the man portable units to large rack mount units using long wire antennas.

3.2 REAL-TIME DGPS COMMUNICATION HARDWARE

The radio communication system possibilities are too diverse to be specifically included in this report. A typical radio set with digital data transmit/receive capability is included in Table 3-1 as well as representative commercial DGPS dedicated units.

3.3 REAL-TIME DGPS COMMUNICATION SOFTWARE

There are basically two types of software that impact real-time DGPS communications, error message protocols, and transmission protocols.

Error message protocols were originally developed by GPS receiver manufacturers and are as diverse as the manufacturers themselves. These error correction message formats are designed to work with the particular manufacturers implementation of position solutions and often contain information that enhances accuracy, but pertains to the functioning of the manufacturer particular equipment only.

In addition, by establishing their own codes manufacturers are able to optimize these codes for their own implementation of transmission methods. The Radio Technical Commission for Maritime Services (RTCM) established Special Committee No. 104 to develop standard real-time DGPS message formats and protocols for vessel navigation purposes. The RTCM SC-104 formats are based on the actual formats for the GPS navigation messages sent from the satellites. This provides versatility across manufacturers designs by establishing a message format that is already handled in one fashion or another by all GPS receivers.

In addition to the original navigation error correction messages, other messages have been developed as a part of the RTCM SC-104 format to support more accurate DGPS corrections. Only

Table 3-1. Typical Real-Time DGPS Radio Equipment

MANUFACTURER	MODEL	MHz FREQUENCY	MODEMS	SIZE	WEIGHT	POWER OUT / IN	RATE	COST	USE
Pacific Crest	PDDR-12	UHF 450-470 VHF 148-168	Internal	4.17w X 6d X 1.52h	1.8 lbs.	2 watts / 9 v Battery Power	300 - 9600 baud	\$545 to \$681	Short Range Data Link
Magnavox	MX 5OR DGPS	VHF 283.5 - 325.0	Internal	5.5w X 6.8d X 1.8h	1.8 lbs.	/ 4.5 w 10-32 VDC	25 - 200 baud	\$5,500	HF Nav Beacon Receiver
Oni	MR401 Micronet Receiver	1.6 - 1.8 MHz	Internal	19 X 5.25 X 17.75	23 lbs.	/ 50 w at 115 VAC	150 baud 1800 Hz	\$16,875	HF Receiver HF Long Range Data Link
Oni	ME401 Micronet Exciter	1.6 - 1.8 MHz	Internal	19 X 3.5 X 17.75	18 lbs.	100 watts / 450 watts at 115 VAC	150 baud 1800 MHz	\$22,950	HF Long Range Data Link
	Amplifier			19 X 5.25 X 17.75	42 lbs.				HF Transmitter

one format can be used at a time, either the RTCM SC-104 format or the manufacturer specific format. Some GPS receivers offer the ability to select either of the formats while other receivers are restricted to one or the other format. Refer to Appendix 1, Special Features column for the capability of a particular receiver to use RTCM SC-104 formats.

The transmission protocols are software and signal structures that support the actual transmission of digital data from any radio transmitter to a radio receiver. The selection of a transmission protocol is a function of the amount of data to be sent, the data rate, and is usually done by the radio system supplier. The transmission protocols should be transparent to the real-time DGPS receivers, acting only as a vehicle to transfer the error correction messages from the base station to the roving receivers.

4. REAL-TIME DGPS PERFORMANCE

The performance of a real-time DGPS system is considerably better than stand alone GPS operations. However, real-time DGPS is restricted to the area of coverage parameters for a particular system and requires the addition of a separate transmit-receive capability. Real-time DGPS is based on the need to provide positioning accuracy in the less than 10 meter range in real-time or near real time operations rather than the accuracies of stand alone GPS. Much higher accuracies (in the subdecimeter range) are available from differential GPS, but only in a time delayed post processed mode.

4.1 REAL-TIME DGPS OPERATIONAL SYSTEMS

Real-time DGPS systems were originally developed to provide:

a. Precise navigation for ships in harbor approach and channel navigation.

b. Precise aircraft positioning for possible precision approach and landing.

c. Precise off shore positioning for underwater exploration (primarily petroleum).

As the usage of GPS became more widespread and the GPS coverage capability grew, more users began finding the need for higher accuracies than GPS alone provided. The implementation of SA and its 100 meter accuracy convinced many users that real-time DGPS was necessary to meet their needs.

Several manufacturers offer real-time differential GPS systems as a package with their equipment tailored to fit the users needs. They usually offer a geodetic quality receiver for the base or monitor station and, dependent upon the accuracy needs, more economical less capable roving receiver units. There are many sales outlets that will tailor a real-time DGPS system to a users needs by selecting various manufacturers equipment and combining them to make a system that not only meets a customers needs, but also integrates any existing equipment into it.

The U.S. Coast Guard (USCG) is developing and deploying real-time DGPS monitor stations that transmit error correction messages via standard navigation radio beacons. This system uses RTCM SC-104 format and is to be available along the coasts and inland waterways of the U.S. To use the USCG system, a GPS receiver and a radio receiver are required. The radio receiver must be capable of receiving the navigation beacon frequency and separating the error correction messages

from the beacon navigation signal. The GPS receiver must be capable of accepting the error correction messages and using them to develop real-time differential GPS position solutions.

There are several precise positioning providers who have integrated real-time DGPS into already existing radio location systems. This integration provides a more robust and in some cases more accurate system.

There is a trend for increased accuracies in real-time DGPS that may eventually lead to first order survey capabilities without post processing. Dual frequency, carrier phase corrected real-time DGPS equipment with sufficient processing capability to apply sophisticated smoothing routines should be available in the near future. As the need for real-time survey quality positioning becomes more apparent, the GPS receiver manufacturers are responding with more capable equipment. Many new receivers with real-time capability are being offered or are on the drawing-board now. <u>Real-time</u> DGPS survey accuracies in the centimeter to decimeter level of accuracy may be very difficult to achieve. However, <u>near</u> real-time (3-5 minute delay) DGPS survey accuracies in the centimeter to decimeter range should be available before 1995.

Table 4-1 lists the suppliers of real-time differential GPS systems along with the expected accuracies of these systems.

Table 4-1. Real-Time DGPS Systems

MANUFACTURER	BASE RECEIVER	REMOTE RECEIVER	UPDATE RATE	ACCURACIES	COST*
Ashtech	DN-12B	DN-12B	.5 second	1 - 3 m	$33,000
		DN-12	.5 second	1 - 3 m	$29,000
	MX11	MX11	.5 second	1 - 3 m	$42,000
		Dimension	1 second	1 - 3 m	$32,495
		Ranger	1 second	1 - 3 m	$38,500
		3DF	1 second	1 - 3 m	$78,500
	P-12	P-12	1 second	1 m or less	$79,000
Del Norte	1008 [1]	1008 [1]	1 second	1 - 5 m	$59,990
		2006 [1]	1 second	1 - 5 m	$44,990
Magnavox	MX-4818 [2]	MX-4800 Series [2]	1 second	2 - 5 m	$55,600
		MX-4200 Series [2]	1 second	2 - 5 m	$32,500
		MX-200 Series [1]	1 second	3 - 5 m	$30,195
	MX-9012R [2]	MX-4800 Series [2]	1 second	2 - 5 m	$42,800
		MX-4200 Series [2]	1 second	2 - 5 m	$19,700
		MX-200 Series [1]	1 second	3 - 5 m	$18,395

Table 4-1. Real-Time DGPS Systems (Continued)

MANUFACTURER	BASE RECEIVER	REMOTE RECEIVER	UPDATE RATE	ACCURACIES	COST*
Motorola	Sixgun 610 [1,2]	Sixgun 610 [1,2]	1 second	2 - 5 m	$ 7,950
		Sixgun 620 [2,3]	1 second	2 - 5 m	$ 8,575
		LGT 1000 [3]	1 second	2 - 5 m	$ 9,975
		Peregrine [1]	1 second	2 - 5 m	$12,550
	Sixgun 620 [1,2]	Sixgun 610 [1,2]	1 second	2 - 5 m	$ 8,575
		Sixgun 620 [2,3]	1 second	2 - 5 m	$ 9,200
		LGT 1000 [3]	1 second	2 - 5 m	$11,100
		Peregrine [1]	1 second	2 - 5 m	$13,175
	LGT-1000 [1]	Sixgun 610 [1,2]	1 second	2 - 5 m	$ 9,475
		Sixgun 620 [2,3]	1 second	2 - 5 m	$11,100
		LGT 1000 [3]	1 second	1 - 5 m	$12,500
		Peregrine [1]	1 second	2 - 5 m	$15,075
Navstar Ltd.	XR4-G	XR4-G	1 second	2 - 5 m [4]	$ 5,990
Sercel	NR-103 [5]	NR-50	.6 second	5 - 10 m	$46,400 [6,7]
		NR-53 [3]	.6 second	3 - 5 m	$52,480 [6,7]
		NR-103 [3]	.6 second	3 - 5 m	$57,550 [6,7]
		NR-106 [1]	.6 second	3 - 5 m	$53,600 [6,7]

Table 4-1. Real-Time DGPS Systems (Continued)

MANUFACTURER	BASE RECEIVER	REMOTE RECEIVER	UPDATE RATE	ACCURACIES	COST*
TOPCON	GP-R1 Series Refer to Appendix 1 options	GP-R1 Series Refer to Appendix 1 options	1 second	3 - 5 m	$37,000 to $107,000
Trimble	Community Base Station	Nav Trac XL	1 second	4 - 7 m	$14,995
		GPS Pathfinder Basic	1 second	2 - 5 m	$17,495
		GPS Basic Plus	1 second	2 - 5 m	$27,000
		GPS-4000 DL II	1 second	2 - 5 m	$25,900
		GPS-4000 RL II	1 second	2 - 5 m	$29,850
	GPS-4000 RL II	Nav Trac XL	1 second	4 - 7 m	$20,845
		GPS Pathfinder Basic	.7 second	2 - 5 m	$23,345
		GPS Basic Plus	.7 second	2 - 5 m	$32,850
		GPS-4000 DL II	.6 second	1 - 3 m	$31,750
		GPS-4000 RL II	.6 second	1 - 3 m	$35,700

* "COST" is the approximate price of GPS equipment only (unless otherwise noted) and does not include the communication links.

1 Includes Internal Modems
2 Requires External PC for control and display
3 Internal radio receiver
4 Low dynamics
5 Includes Transmitter - UHF, HF, or Dual HF
6 Add $4,000 for HF option
7 Add $62,000 for Dual HF

5. COST ANALYSIS

The actual pricing of a real-time DGPS system is beyond the scope of this study. Such a price breakdown is dependent upon the actual user requirements. However, the elements and considerations to determine a system cost will be discussed in the following paragraphs with the primary focus dealing with system equipment acquisition.

5.1 COST ANALYSIS CONSIDERATIONS

The main elements that determine a system cost are the equipment acquisition costs, the operational and maintenance costs, the training costs, and the interface costs. The interface costs are those costs associated with taking the output data from the real-time DGPS system and converting it into a product usable by the customer. The training costs and the operational and maintenance costs need to be determined in light of the already existing BLM infrastructure. The equipment acquisition costs are a function of how the system will be used and what the customers specific requirements are.

The equipment necessary to provide a real-time DGPS system usually includes:

a. A base or monitor station GPS receiver.

b. One or more roving GPS receivers.

c. A base or monitor station radio transmitter.

d. One or more radio receiver units to correspond with the roving GPS receivers.

e. A peripheral data processing capability (usually at the monitor station) to perform error correction analysis.

f. An antenna system to support the monitor station transmitter.

Additional equipment may be required based upon the system use. Typical uses for real-time DGPS in the BLM include:

a. Logging and mining observation.

b. Navigation.

c. Flight following.

d. Aerial photogrammetry

e. Range surveillance.

f. Road mapping.

g. Land boundary determination.

h. Law enforcement.

i. Corner marker location.

j. Wetland monitoring.

k. Environmental observation.

l. Fire control and monitoring.

These uses have requirements that drive the system design. The system design is usually a function of accuracy, dynamics, the radio system, and the area of coverage.

5.1.1 Accuracy

The accuracy requirements for a real-time DGPS receiver affect the cost of the system in several ways. The items that determine the accuracy of a GPS receiver include:

a. The number of channels.

   The more channels a GPS receiver contains the more potential accuracy the system has. Channels drive cost. The more channels or receivers the unit has, the more complex the receiver must be, and the more it costs. (Typically 10 - 15% per channel over the base 1 to 2 channels.)

b. The capability to use both C/A-code and P-code.

   The use of both C/A and P-code gives the potential for sub 5 meter accuracies with essentially dual processing capability required. Increased costs are from 30 - 50% higher for adding P-code capability.

c. The capability for both C/A-code and P-code dual frequency GPS reception.

   The use of both C/A and P-code dual frequency increases accuracy by decreasing atmospheric transmission errors. The internal complexity to receive both codes, process atmospheric corrections, and process dual code position fixes results in increased cost (usually between 40 - 100% more).

d. The capability for carrier phase processing.

   Carrier phase processing is a software intensive technique that requires increased

internal processing capability and brings accuracies within the 1 - 3 meter range. Carrier phase processing usually adds about 50% to the cost of a GPS receiver.

e. Increased update rate.

The more often a position is calculated the more accurate the position fixes will be and the better that smoothing routines will work with the positional data. Increasing the update rate to less than 1 sec requires an increase in processing capability and speed resulting in a 10 - 30% increase in cost.

f. Increased transmission rate.

The higher the rate that data is transmitted from and received by a real-time DGPS system the more error correction messages can be sent. This is often necessary to support carrier phase correction messages and results in higher accuracy and an increase in cost of from 10 - 50% depending on the speed requirements and internal receivers changes.

The impacts of accuracy requirements are the greatest factors affecting the cost of the GPS receiver equipment.

5.1.2 Dynamics

The dynamics requirements of the real-time DGPS system are related to the accuracy requirements of the system. The greater the accuracy of the system generally, the less dynamically capable the system is. As the dynamic requirements increase with high accuracy requirements, the cost of the system increases. The factors that drive this increase in cost are:

a. Data transmission rates.

The higher the data transmission rate, the more messages can be received in a given period of time and consequently, the higher the dynamic response. Increasing the data transmission rate has impact primarily on the communication link between the base or monitor station and the roving receivers. The typical cost increase involved is around 10 - 20% for the radio system.

b. Increased update rate.

An increase in update rate increases the number of positions generated in a given period

of time. This offsets the drift in accuracy as a function of time as well as the change in position of a highly dynamic vehicle. This increase directly impacts the receiver processing rate and capability that can result in a 10 - 30% increase in receiver costs.

c. Increased internal storage of messages.

As an alternative to increasing the data transmission rate of the radio system, the storage of GPS navigation data messages within the receiver may be increased. This storage increase along with increased processing capability allows an enhanced smoothing of data to be applied that can impact both accuracy and dynamic capability. This change in receiver capability can increase cost from 10 - 30%.

Dynamic capabilities of a real-time DGPS system are primarily a function of the radio system transmission rates and of the update rate of the GPS receiver. Cost impacts for high dynamics generally impact the entire system by around 15 percent.

5.1.3 The Radio System and the Area of Coverage

The radio system requirements can have a significant impact on the overall cost of a real-time DGPS system. On one hand, if a "public" system such as that being developed by the USCG is used, cost to other than the developers is minimal, requiring only an HF radio receiver and a real-time DGPS receiver. However, if a stand alone real-time DGPS system is necessary, because of accuracy requirements or the geographical location of use, the radio communication system becomes a significant element of the overall system. The radio communication system and the area of coverage are inseparable.

The area of coverage requirements drive the primary design of the radio system. The elements that need to be considered when designing or selecting a real-time DGPS communication system include:

a. The range requirement.

The greater the range, the higher the cost. To achieve longer ranges (beyond line-of-sight) for a real-time DGPS system, the communication system must have a higher power output and a relatively low frequency (HF/low VHF). These characteristics

impact the antenna design and the portability of the system as well as increasing the cost.

b. The terrain impact.

To make a real-time DGPS system relatively terrain independent, the transmitting antennas should be positioned such that a relatively unrestricted line-of-sight is available to the roving receivers. If this is not possible, then, as in extended range requirements, a lower frequency and higher power output are required along with increased costs.

c. The use of multiple frequencies.

To improve the error free transmission rate of a real-time DGPS system, the error correction messages are sent and received simultaneously on two different frequencies. Thus if one frequency is attenuated by local disturbances the other may be free of interference. In addition, if both frequencies are free, a simple comparison routine ensures accuracy of the messages. This capability becomes significant as data rates exceed 9600 baud. The cost of dual frequency communications is generally 30 - 80% higher than single frequency systems.

d. Portability requirements.

The more portable a system must be, generally, the more it will cost for a given level of performance. For low power, low capable, line of sight systems, the portability has little impact. As the performance requirements increase, however, the cost of portability increases and for high performance systems, can be a limiting factor.

e. Piggy-back transmissions.

One way to reduce the cost of a real-time DGPS system is to transmit error correction messages over an unused portion of an already existing radio broadcast system. The USCG system piggy-backs on the existing HF coastal navigation beacons. A system has been proposed that would piggy-back DGPS error correction messages on the unused upper frequencies of commercial FM radio stations. These methods can significantly expand the area of coverage (when networking techniques are used) while

eliminating the cost of a stand alone transmitting system. But may not satisfy other system needs for accuracy and dynamics.

The other major factor to be considered in the radio system design, the data transmission rate, has been discussed in 5.1.1 and 5.1.2. The selection of the radio communication system equipment should take into consideration any existing equipment in the customers inventory that may be used, and any existing frequency allocations from the FCC.

5.2 SYSTEM COSTS

Based upon the selected system design, the cost of the system reflects the complexity and capability of the equipment used (i.e., the more complex and capable the system, the higher the cost). The proportional increases in cost for increased capabilities are tending to decline as competition and equipment maturity are forcing the overall price of GPS receivers down. Refer to Appendix 1 for the costs of currently available real-time capable DGPS receivers. These costs are based on manufacturers suggested retail price and in some cases are considerably less when purchased through General Services Administration (GSA).

6. TRAINING

Training becomes more important as overall resources become more scarce. Efficient operations require that to effectively use the personnel available, the knowledge base of the personnel must include a thorough understanding of the material and system resources available to them. The utility of a real-time DGPS system is dependent upon the capabilities of the people using the system. The more they understand the system, the fewer the mistakes and the better the operational results will be. Training is the basis of this understanding.

6.1 REAL-TIME DGPS SYSTEM TRAINING

Training for use of a real-time DGPS system should include basic real-time DGPS theory, equipment set up, base station operation, and roving receiver operation.

6.1.1 Basic Real-Time DGPS Theory

The curriculum for basic real-time DGPS training should include fundamental instruction in the following areas:

a. GPS positioning

b. Differential GPS positioning

c. Real-time DGPS positioning

d. Factors that affect real-time DGPS positioning

e. Practical uses of real-time DGPS

f. Post-processing of real-time DGPS data for higher accuracy

g. Integration of real-time DGPS data into existing products

6.1.2 Equipment Set-Up

Training for the equipment set-up of the real-time DGPS system should include instruction in the following areas:

a. Selection and identification of the pre-surveyed base or control point

b. Selection of the antenna site and set-up (GPS and transmitter)

c. Power connections

d. Antenna cable hook ups (GPS and transmitter)

e. Modem connections

f. Transmitter/Receiver hook ups

g. Mobile equipment hook ups

h. Auxiliary processor hook ups (if required)

6.1.3 Base Station Operation

Training for the operation of the base station should include review of the operations manuals from the specific equipment manufacturers as well as instruction in the following areas:

a. Operating hours

b. Monitoring requirements

c. Expected operating equipment conditions and settings

d. Software loading procedures

e. Initial program loading procedures

f. Abnormal operation procedures

g. Basic troubleshooting

h. System test procedures

6.1.4 Remote Receiver Operations

Training for the operation of the roving or remote receiver units should include instruction in the following areas:

a. Review of manufacturer operation manuals

b. System self test and verification

c. Expected equipment conditions and settings

d. Abnormal equipment conditions and settings

e. Basic troubleshooting

f. Field use procedures

g. Information use and significance

6.2 TRAINING RECOMMENDATIONS

The training of BLM personnel for the use of a real-time DGPS system should be conducted using three basic methods (i.e., classroom instruction, computer based training, and hands-on training).

6.2.1 Classroom Training

The classroom training for real-time DGPS should be the primary method for teaching the system theory. This training should be video taped for use in remote regions where a classroom training course may be impractical to conduct. In addition, the classroom method should be used at least as an overview for equipment set-up and the actual field operations. The classroom training can be augmented by training supplied by the equipment manufacturers.

6.2.2 Computer Based Training

Computer Based Training (CBT) should be used to enhance specific knowledge areas. It can be used as augmentation of classroom training for the real-time DGPS theory, but would have the most impact in the areas of operational procedures and equipment setup. Properly developed computer based interactive training which delivers information in intuative, multisensory ways through the integration of text, graphics, animation, video, and sound, in a single presentation under the control of a computer has been proven to increase information retention and reduce system operator errors. Additional benefits realized from CBT include a stabalized knowledge base and increased efficiency, effectiveness, and standardization. This type of training once developed can easily be given to the field operations personnel on an as required basis.

6.2.3 Hands-On Training

Hands-on training is an essential method of training to generate familiarity with equipment operations. The aspects of equipment set-up and both base and remote operations should include thorough hands-on familiarization for the operators. Instructional material to help in hands-on training should also be available from the equipment manufacturers.

7. SUMMARY

This report is a broad overview of the present capabilities of real-time DGPS and the equipment necessary to field such a system. It provides a review of the capabilities of currently available commercial real-time DGPS equipment based on the manufacturers sales literature. An in-depth study of each of the systems capabilities is required prior to selection of a system for BLM use. In addition, the systems presented are based on the base or monitor station and the remote or roving receivers being supplied by the same manufacturers. There are many combinations of equipment that can be used to provide a real-time DGPS system as long as a common error correction message format is supported. However, it must be taken into consideration that a system will only be as capable as its least capable component. The following areas were specifically addressed in this report.

7.1 GPS STATUS

The current status of the GPS constellation through SVN #32 is presented in Section 1. Section 1 also includes an overview of the GPS structure, the specified GPS signal accuracies and availability, an overview of SA/AS, and the projected launch schedule required to complete the GPS constellation.

7.2 REAL-TIME DGPS CAPABILITIES

A basic review of the various GPS positioning techniques is presented in Section 2, including stand-alone GPS positioning, differential GPS positioning, and real-time differential GPS positioning. The capabilities of each of these techniques is explored in detail. Emphasis is given to the real-time DGPS capabilities and what is theoretically possible from this type of system as well as what has been observed in practical applications.

7.3 REAL-TIME DGPS RECEIVER HARDWARE AND SOFTWARE

Real-time DGPS receiver hardware is discussed in Sections 2 and 4 and is presented in a tabular format in Appendix 1. A table of real-time DGPS systems is presented in Section 4. These systems are single manufacturer designs and do not include the multiple combinations that are possible by selecting equipment from various manufacturers. The software that is available for these

systems is primarily manufacturer developed and specific. A listing of this software and some of the interface software is included in Section 2.

7.4 REAL-TIME DGPS COMMUNICATIONS EQUIPMENT

The radio communications equipment possibilities necessary to support a real-time DGPS system are too diverse to be included in this report. However, the system considerations necessary to select a communication system are discussed in Sections 2, 3, and 5. Some representative real-time DGPS communications equipment is included in Section 3.

7.5 COST CONSIDERATIONS

The elements required to determine the cost of a real-time DGPS system are discussed in Section 5. The actual cost of the system will depend upon the requirements and equipment selection. Section 5 includes a comparative cost impact of various system requirements.

7.6 TRAINING RECOMMENDATIONS

As discussed in Section 6, three types of instructions are recommended for BLM training in real-time DGPS systems operations (i.e., classroom training, computer based training, and hands-on training).

APPENDIX 1

REAL-TIME DGPS RECEIVERS

MANUFACTURERS OF REAL-TIME DGPS RECEIVERS

Ashtech Inc.
1170 Kifer Road
Sunnyvale, CA 94086
Phone: (408) 524-1400
Fax: (408) 524-1500

Del Norte Technology Inc.
1100 Pamela Drive
P.O. Box 696
Euless, TX 76039
Phone: (817) 267-3541
Fax: (817) 354-5762

Honeywell
P.O. Box 21111, MS: K19B4
Phoenix, AZ 85036
Phone: (602) 436-1677
Fax: (602) 436-2252

Magellan Systems Corp.
960 Overland Court
San Dimas, CA 91773
Phone: (714) 394-5000
Fax: (714) 394-7050

Magnavox GPS
2829 Maricopa Street
Torrance, CA 90503
Phone: (310) 618-1200
Fax: (310) 618-7001

Motorola Inc.
Government Electronics Group
8201 E. McDowell Road
P.O. Box 1417
Scottsdale, AZ 85252-1417
Phone: (800) 424-0052
Fax: (602) 441-6702

Navstar Electronics Inc.
1500 North Washington Blvd.
Sarasota, FL 34236
Phone: (800) 486-6338
Fax: (813) 366-9335

Prakla-Seismos AG
Buchholzer Str. 100
D-3000 Hannover 51
Germany
Phone: +49(5)11-6420
Fax: +49(5)11-6476860

Rauff & Sørensen A/S
Shipmate

Robertson-Shipmate
400 Oser Ave.
Hauppauge, NY 11788
Phone: (516) 231-3000
Fax: (516) 231-3178

Sercel Incorporated - USA
17155 Park Row
P.O. Box 218909
Houston, TX 77218
Phone: (713) 492-6688
Fax: (713) 492-6910

Topcon America Corp.
6940 Knoll Center
Pleasanton, CA 94566
Phone: (510) 417-0107
Fax: (510 417-0130

Tremetrics Inc.
2215 Grand Avenue Parkway
Austin, TX 78728
Phone: (512) 251-1400
Fax: (512) 251-1596

Trimble Navigation, Ltd.
645 N. Mary Avenue
Sunnyvale, CA 94086
Phone: (408) 481-6915
Fax: (408) 481-6074

NOTE: The information in this appendix is current as of 15/OCT/92 and is based on manufacturer supplied data.

REAL-TIME DGPS RECEIVERS

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE / UPDATE	SPECIAL FEATURES	PRICE
Ashtech Dimension	12 C/A code carrier	1992	4.1 w 8.32 VDC	3.2 lbs.	9.3" circular x 1.7" thick	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 / 1 per second	RTCM-104 Ashtech Remote only	w/carrier \$ 8,995 w/o carrier \$ 5,995 Plus R-T opt. \$ 2,500
Ashtech M-X11	12 C/A code carrier	1989	12 w 18 - 36 VDC	8.2 lbs.	8.0 x 8.5 x 3.9"	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 / 1 per second	RTCM-104 Ashtech Base/Remote 1/4 sec avail 1/2 sec avail	C/A \$21,000 C/A & P \$27,000 Plus R/T opt. \$ 2,500
Ashtech P-12	12 C/A-code P-code carrier	1992	12 w 10-36 VDC	8.2 lbs.	8.0 x 8.5 x 3.9"	R-T 1 m or less P-code 20 m	2 RS-232 / 1 per second	RTCM-104 Ashtech Base/Remote Dual Freq P-code	\$37,000 Plus R-T opt. \$ 2,500
Ashtech DN-12	12 C/A-code	1992	10 w 10-36 VDC	8.2 lbs.	8.0 x 8.5 x 3.9"	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 / 1/2 second	RTCM-104 Ashtech Base/Remote 1/4 sec avail	base \$16,500 remote \$12,500
Ashtech 3 DF	24 C/A-code carrier	1990	10 w 10-36 VDC	9 lbs.	8.0 x 8.5 3.9"	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 / 1 per second	RTCM-104 Ashtech Remote only attitude air-craft capable opt.	\$55,000 Plus R-T opt. \$ 2,500
Ashtech Ranger	12 C/A-code	1992	10 w 10-36 VDC	8.2 lbs.	8.0 x 8.5 x 3.9"	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 / 1 per second	RTCM-104 Ashtech Remote only	\$15,000 Plus R-T opt. \$ 2,500

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE / UPDATE	SPECIAL FEATURE	PRICE
Del Norte 1008	8 C/A-code	1990	60 w 11-28 VDC	36 lbs.	20.5 x 17.5 x 7.5"	R-T 1-5 m C/A 25 m (NO/SA)	6 serial ports / 1 per second	RTCM-104 Del Norte Base/Remote Internal 386-PC, Internal modem, micro-wave ranging capable	$29,995
Del Norte 2006	6 C/A-code	1992	60 w 11-28 VDC	36 lbs.	20.5 x 17.5 x 7.5"	R-T 1-5 m C/A 25 m (NO/SA)	6 serial ports / 1 per second	RTCM-104 Remote only Internal 386-PC	$14,995
Honeywell ELAC-Nautik GMBH GPS-8800	5 C/A-code	1989	40 w 12-24 VDC	26 lbs.	13.4 x 14.3 x 6.3"	R-T 2-3 m C/A 25 m (NO/SA)	2 RS-232 ports / 1 per second	RTCM-104 Remote only	$15,000
Magellan GPS NAV 5000 PRO	5 C/A-code carrier	1992	1.59 w 8-16 VDC	30 ounces	8.75 x 3.5 x 2.13"	R-T 5-10 m C/A 25 m (NO/SA)	RS-232 port / 1 per second	RTCM-104 Remote only Rinex capable	$ 3,750
Magnavox MX4818 (To be discontinued in 1993)	12 C/A-code carrier	1989	34 w 22-30 VDC	9.5 lbs.	8.6 x 5.0 x 11.0"	R-T 2-5 m C/A 25 m (NO/SA)	2 RS-422 NMEA0183 / 1 per second	RTCM-104 Base only Requires ex-ternal PC for control & display	$27,800

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE UPDATE	SPECIAL FEATURE	PRICE
Magnavox MX 9012R	12 C/A-code carrier	1992	5 w 10-32 VDC	2 lbs.	1.8 x 5.5 x 6.75"	R-T 1-3 m C/A 25 m (NO/SA)	2 RS-232 2 RS-422 1 per second	RTCM-104 Base only Internal modem Requires ex- ternal PC for control & display	$15,000
Magnavox MX 200	6 C/A-code	1992	1 w 10.5-32 VDC	2.5 lbs.	2 x 5.9 x 11.75"	R-T 3-5 m C/A 25 m (NO/SA)	10 ports NMEA0183 NMEA 0180 1 per second	RTCM-104 Remote only Maritime	$ 3,395
Magnavox MX 4200 Series	6 C/A-code carrier	1990	3.5 w 10-32 VDC	2 lbs.	1.8 x 5.5 x 6.75"	R-T 2-5 m C/A 25 m (NO/SA)	3 RS-422 NMEA 0183 1 per second	RTCM-104 Remote only Requires ext- ernal PC for control & display	$ 4,700
Motorola Sixgun 610	6 C/A-code carrier	1992	3 w 8-30 VDC	< 2 lbs.	7 x 5.7 x 1.8"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 2 RS-422 NMEA 0183 1 per second	RTCM-104 Motorola Base/Remote Internal modem Requires ext- ernal PC for control & display	$ 3,975

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE / UPDATE	SPECIAL FEATURE	PRICE
Motorola Sixgun 620	6 C/A-code carrier	1992	10 w 10-30 VDC	< 2 lbs.	7 x 5.7 x 1.8"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 RS-422 NMEA 0183 / 1 per second	RTCM-104 Motorola Base/Remote Internal VHF/ UHF Radio Requires ext-ernal PC for control & display	$ 4,600
Motorola LGT1000	6 C/A code carrier	1992	3 w 7.5 VDC	< 2.5 lbs.	7.88 x 4.08 x 2.5"	R-T 1-5 m	2 RS-232 NMEA 0183 / 1 per second	RTCM-104 Motorola Base/Remote Internal VHF/ UHF Radio GIS features	Base $ 6,500 Remote $ 6,000
Motorola Peregrine	6 C/A-code	1992	20 w 15-35 VDC	8 lbs.	8.3 x 3.8 x 6.9"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 NMEA 0180 NMEA 0183 / 1 per second	RTCM-104 Motorola Remote only Internal modem Tracking applications	$ 8,575
Navstar Ltd. XR4-G DGPS	2 C/A-code carrier	1992	9 w 9-40 VDC	5.5 lbs.	5.5 x 9.4 x 5.5"	R-T 2-5 m C/A 25 m (NO/SA)	2 RS-232 NMEA 0180 NMEA 0182 NMEA 0183 FURUNO CIF / 1 per second	RTCM-104 Base or Remote	$ 2,995
Prakla-Seismos AG GPS 8800	5 C/A-code	1989	40 w 12-24 VDC	26 lbs.	13.4 x 14.3 x 6.3"	R-T 2-3 m C/A 25 m (NO/SA)	2 RS-232 ports / 1 per second	RTCM-104 Remote receiver only	$15,000

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE / UPDATE	SPECIAL FEATURE	PRICE
Rauff & Sorensen Shipmate RS 5300C	5 C/A--code	1991	9 w 10-43 VDC	5 lbs.	10.12 x 3.27 x 6.22"	R-T 5-8 m C/A 25 m (NO/SA)	NMEA 0180 NMEA 0182 NMEA 0183 printer 1 per second	RTCM-104 Remote only requires shipmate RS5360 DR Receiver	$ 3,000
Sercel NR 50	5 C/A-code carrier	1991	12 w 10-36 VDC	11 lbs.	9.2 x 5.6 x 11.6"	R-T 5-10 m C/A 25 m (NO/SA)	RS-232 NMEA 0182 NMEA 0183 .6 seconds	RTCM-104 Sercel Remote only	$ 8,400
Sercel NR 53	5 C/A-code carrier	1991	12 w 10-36 VDC	11 lbs.	9.2 x 5.6 x 11.6"	R-T 3-5 m	2 RS-232 NMEA 0182 NMEA 0183 1 serial port .6 seconds	RTCM-104 Sercel Remote only built in radio receiver	$14,480
Sercel NR 103	10 C/A-code carrier	1991	12 w 10-36 VDC	11 lbs.	9.2 x 5.6 x 11.6"	R-T 3-5 m C/A 25 m (NO/SA)	2 RS-232 NMEA 0182 NMEA 0183 1 serial port .6 seconds	RTCM-104 Sercel Base/Remote built in radio receiver opt. w/xmtr Base - UHF Base - HF Base - Dual HF	Remote $19,550 Base - UHF $38,000 Base - HF $42,000 Base -Dual HF $100,000
Sercel NR106	10 C/A-code carrier	1992	~12 w 10-36 VDC	11.3 lbs.	10.8 x 10.8 x 5.3"	R-T 3-5 m C/A 25 m (NO/SA)	2 RS-232 NMEA 0182 NMEA 0183 .6 seconds	RTCM-104 Sercel Remote only Internal modem	$15,600

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE UPDATE	SPECIAL FEATURE	PRICE
Top Con Corp. GP-R1 Series	12 C/A-code Dual Freq P-code	1990	12 w 10-36 VDC	8.2 lbs.	8 x 8.5 x 4"	R-T 3-5 m C/A 25 m (NO/SA)	2 RS-232 .5 seconds	RTCM-104 Base/Remote Opt. Dual-Freq P-code Photogmtry	$25,000 plus R-T Remote $ 2,500 R-T Base $ 4,500 Dual Freq $20,000 P-code $ 5,000 Photogmtry $ 3,500
Tremetrics Globestar DGPS	2 C/A-code	1992	10 w 10-40 VDC	8 lbs.	13 x 12.75 x 4.5"	R-T 5-10 m C/A 25 m (NO/SA)	RS-232 NMEA 0183 1 per second	RTCM-104 Remote only Internal Nav Beacon rec- eiver, Low dynamic	$ 8,995
Trimble Nav Trac XL GPS	6 C/A-code	1992	12 w 12, 24 VDC	4.5 lbs.	2.75 x 9 x 6.5"	R-T 4-7 m C/A 25 m (NO/SA)	2 RS-422 NMEA0183 NMEA0180 1 per second	RTCM-104 Remote only	$ 2,995
Trimble GPS Pathfinder Basic	3 C/A-code	1992	3 w 8.4-12 VDC	4.2 lbs.	7 x 6.5 x 2"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 .7 second	RTCM-104 Remote only	$ 5,495
Trimble GPS Basic Plus	6 C/A-code	1992	3 w 8.4-12 VDC	4.2 lbs.	7 x 6.5 x 2"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 .7 second	RTCM-104 Remote only	$15,000
Trimble GPS Community Base Station	6 C/A-code	1990	3 w 10.5-35 VDC	2.75 lbs.	8.2 x 2 x 5"	R-T 2-5 m C/A 25 m (NO/SA)	RS-232 1-15 seconds	RTCM-104 Base only	$12,000

REAL-TIME DGPS RECEIVERS (Continued)

MANUFACTURER MODEL	CHANNELS	DATE INTRO.	POWER W/V	WEIGHT	SIZE LxWxH	ACCURACY	INTERFACE / UPDATE	SPECIAL FEATURE	PRICE
Trimble GPS 4000 DL II	9 C/A-code	1991	5 w 10.5-35 VDC	6 lbs.	11 x 9.8 x 4"	R-T 1-3 m C/A 25 m (NO/SA)	RS-232 NMEA0183 / .5 second	RTCM-104 Remote only Opt. 12 channel	$13,900
Trimble GPS 4000 RL II	9 C/A-code carrier	1991	5 w 10.5-35 VDC	6 lbs.	11 x 9.8 x 4"	R-T 1-3 m C/A 25 m (NO/SA)	RS-232 NMEA0183 / .6 second	RTCM-104 Opt. 12 channel Base/Remote	$17,850

APPENDIX 2

LIST OF ACRONYMS AND ABBREVIATIONS

LIST OF ACRONYMS AND ABBREVIATIONS

2-D	Two dimensional
3-D	Three dimensional
AFB	Air Force Base
AS	Anti-spoofing
BLM	Bureau of Land Management
C/A-code	Coarse acquisition code
CEP	Circular error probable
DGPS	Differential Global Positioning System
DOD	Department of Defense
DMA	Defense Mapping Agency
DSCS	Defense Satellite Communications Systems
FOC	Full Operational Capability
FRP	Federal Radio-Navigation Plan
GAs	Ground Antennas
GIS	Geographic Information Systems
GPS	Global Positioning System
GSA	General Services Administration
IODE	Issue of Data Ephemerides
LCC	Leased Common Carrier
MCS	Master Control Station
NAV	Navigation
MSs	Monitor Stations
NDS	Nuclear Detection System
NUDET	Nuclear Detonation
OCS	Operational Control System
OPSCAP	Operations capability
P-code	Precision code

LIST OF ACRONYMS ABBREVIATIONS (Continued)

PCS	Prelaunch Compatibility Station
PPS	Precise Positioning Service
PRN	Pseudo-random noise
RTCM	Radio Technical Commission Maritime Services
SA	Selective availability
SC-104	Special Committee-104
SEP	Spherical Error Probable
SOH	State-of-health
SPS	Standard Positioning Service
SS	Space Segment
SV	Space Vehicle
SVN	Space Vehicle Number
USCG	United States Coast Guard
USNO	United States Naval Observatory
Y-code	Encrypted version of P-code